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# Analysis the "HiFoot" Campaign Fusion Neutron Spectra at the NIF

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# Analysis the “HiFoot” campaign fusion neutron spectra at the NIF

57th Annual Meeting of the APS Division of Plasma Physics

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### **Abstract:**

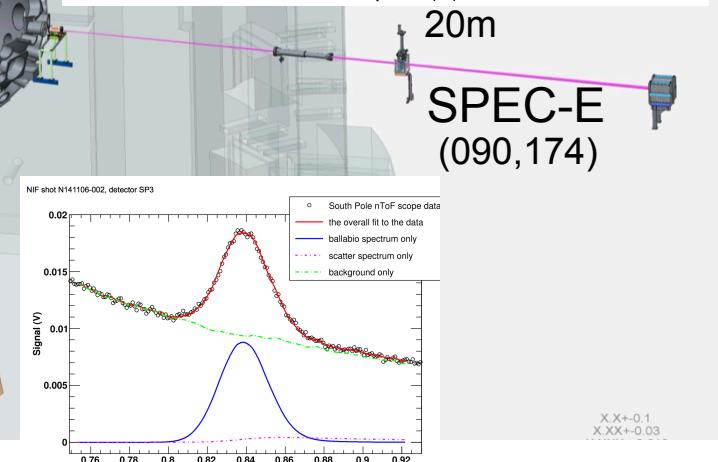
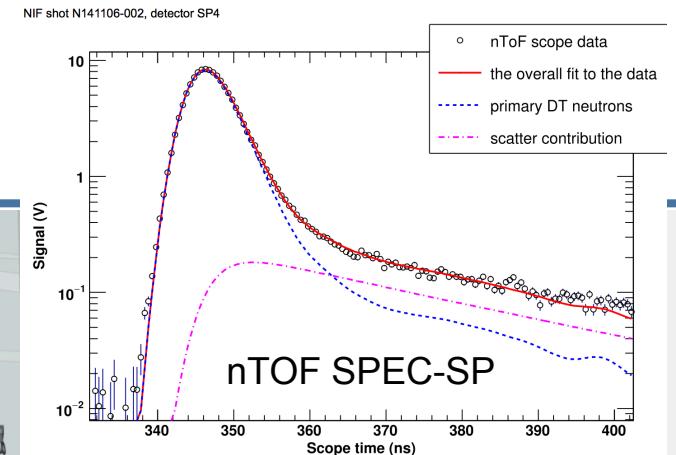
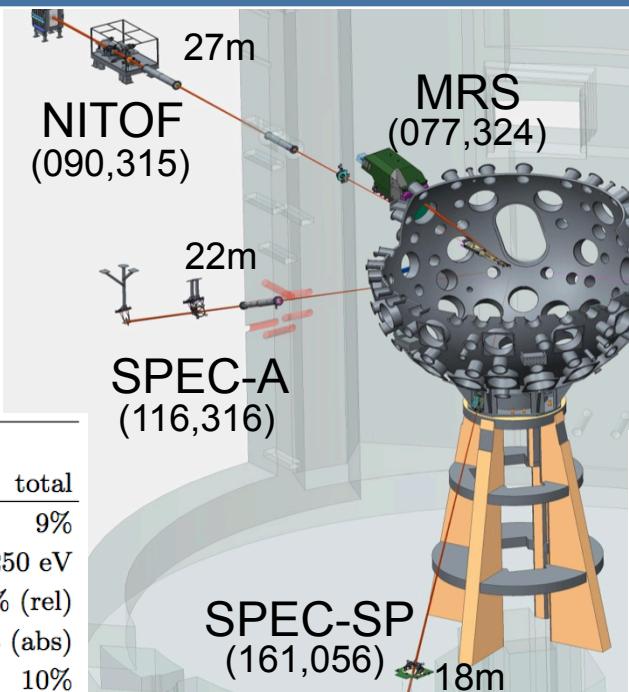
High convergence implosions introduce a number of factors having significant effects on the analysis of high precision reactant neutron time-of-flight (TOF) spectra at the NIF. Low mode perturbations of both the spatial and velocity distributions of the hot-spot and the cold-fuel are measurable in this data set. We report on the analysis performed to date including the line-of-sight (LOS) variation of “standard observables” (e.g. the yield and ion temperature) as well as new analysis extracting the bulk hot-spot velocity and the hot-spot velocity variance. These observations indicate that the assumption of isotropy of reactant neutrons can no longer provide an accurate description of the data. Preliminary analysis of the NIF “high foot” campaign data will be reported. We will describe the direction of future nuclear diagnostic techniques.

# Precision neutron spectrum

Current TOF analysis is dominated by systematic uncertainties presumed to be largely from the Instrument Response.

## nTOF SPEC

| Quantity     | statistical | uncertainty<br>systematic     | total                         |
|--------------|-------------|-------------------------------|-------------------------------|
| DT $Y_n$     | < 1%        | 9%                            | 9%                            |
| DT $T_{ion}$ | ≈ 1%        | 240 eV                        | 250 eV                        |
| DSR          | ≈ 5%        | ≈ 5% (rel)<br>and 0.003 (abs) | ≈ 7% (rel)<br>and 0.003 (abs) |
| DD $Y_n$     | ≈ 2%        | 10%                           | 10%                           |
| DD $T_{ion}$ | ≈ 2%        | 270 eV                        | 290 eV                        |



Well characterized measurements of neutron kinetic energy spectrum from the implosions along multiple lines of sight.

## Observables

model of detector output

$$f(t) = I(E(t))s(E(t))a(E(t))\frac{dE}{dt} \otimes R(t)$$

↑  
sensitivity      attenuation      Instrument response

$$I(E) = A \left( I_{src}(E) + \frac{1}{2} f_{scat} (I_{d\_scat}(E) + I_{t\_scat}(E)) \right)$$

$$I_{src}(E) = \frac{1}{\sqrt{2\pi}\sigma^2} \exp \left( -\frac{2\bar{E}}{\sigma^2} \left( \sqrt{E} - \sqrt{\bar{E}} \right)^2 \right)$$

$$\langle E \rangle = E_0 + \Delta E_{th}$$

Sets TOF for *velocity*

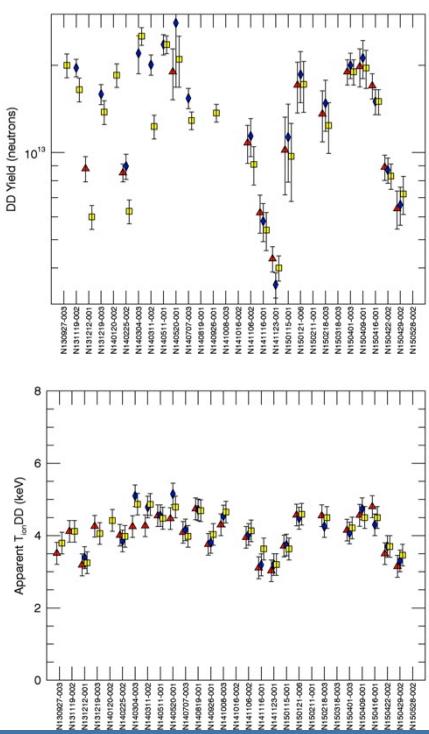
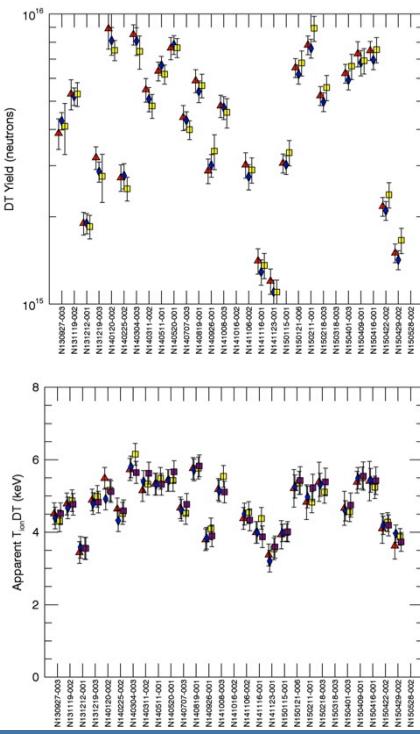
$$\langle (E - \langle E \rangle)^2 \rangle = 4E_0 \frac{m_n}{m_n + m_r} (1 + \delta_w) T_{ion}$$

*Yield* is charge integrated over DT signal region (“Total Yield” is corrected for scattering.

Down Scatter Ratio, *DSR*, is ratio of the 10-12 MeV and 13-15 MeV integrals of spline fit.

Model presumes the form for a space-and-time-constant temperature-and-density plasma at equilibrium.

# Yield and apparent ion temperature

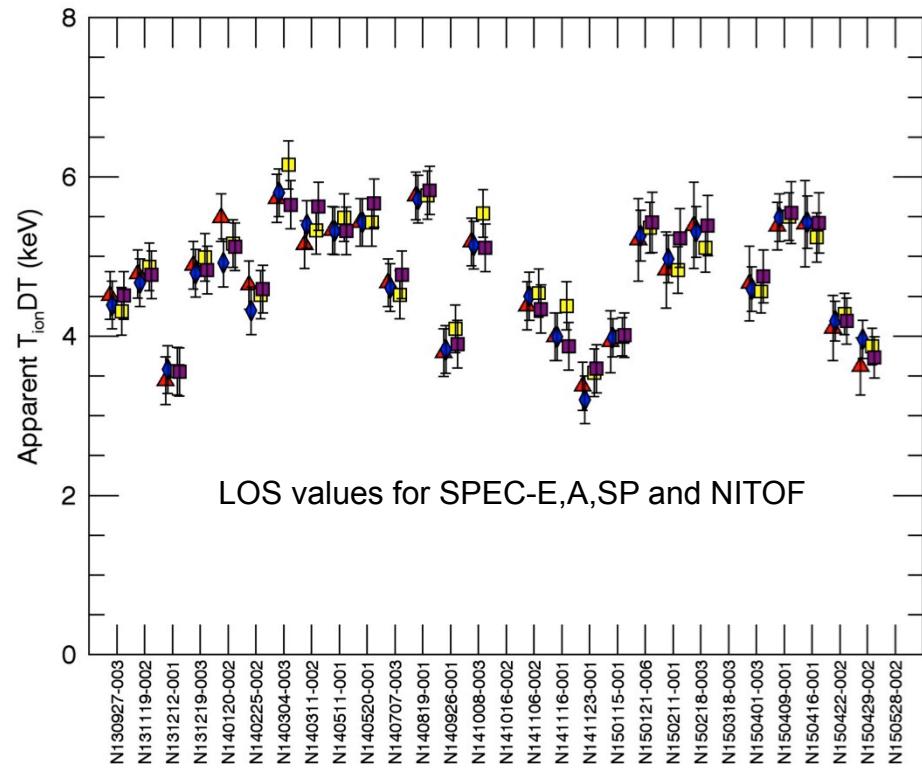
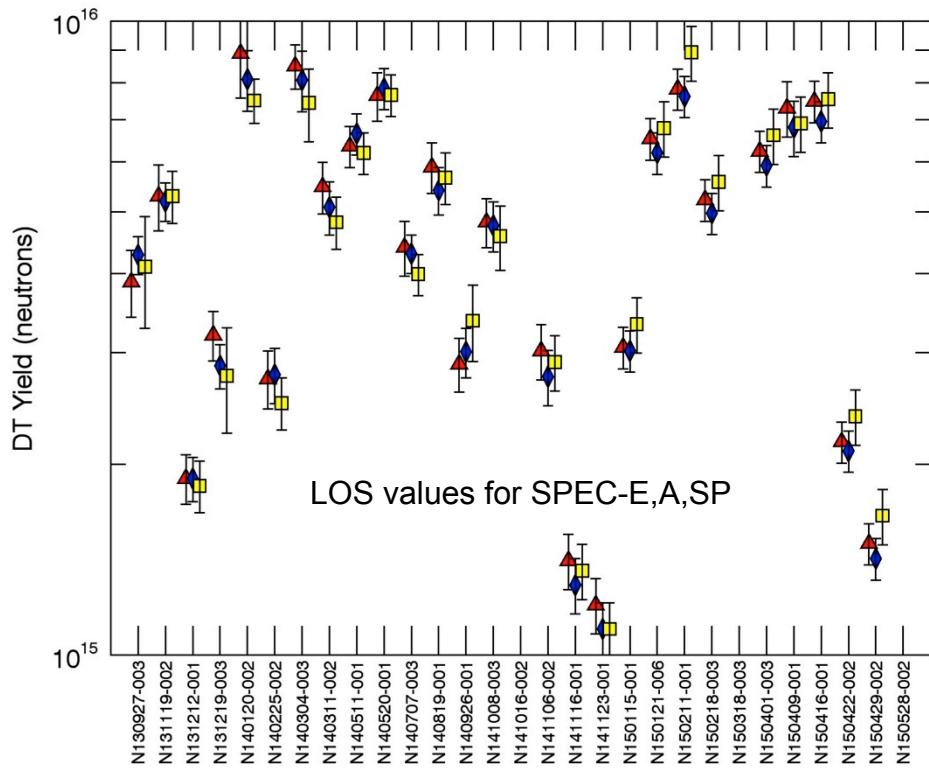


“By eye”

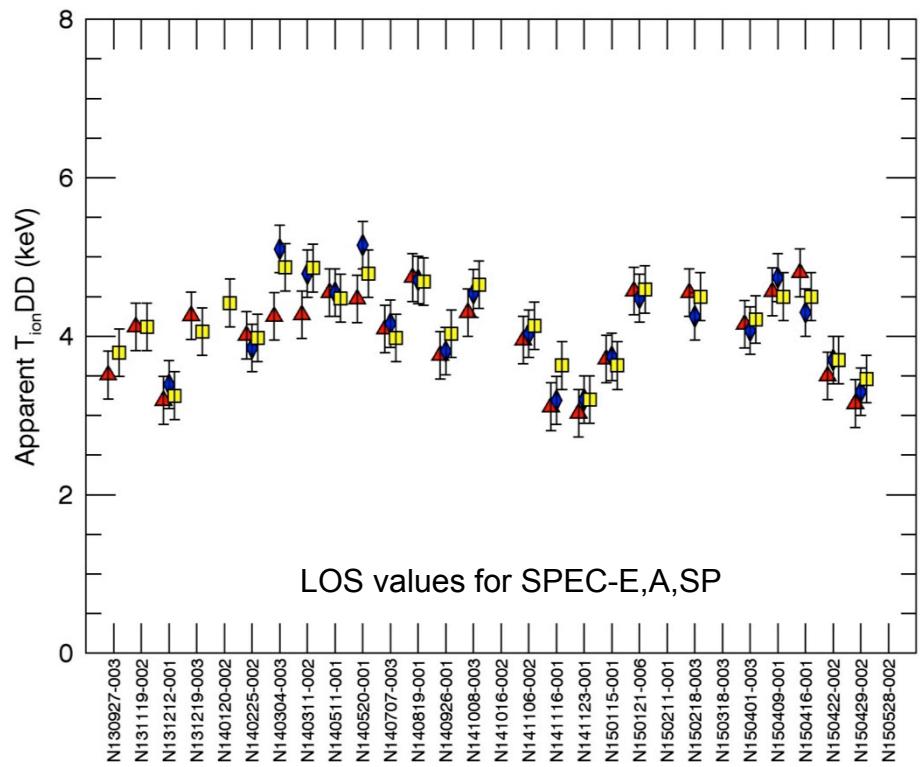
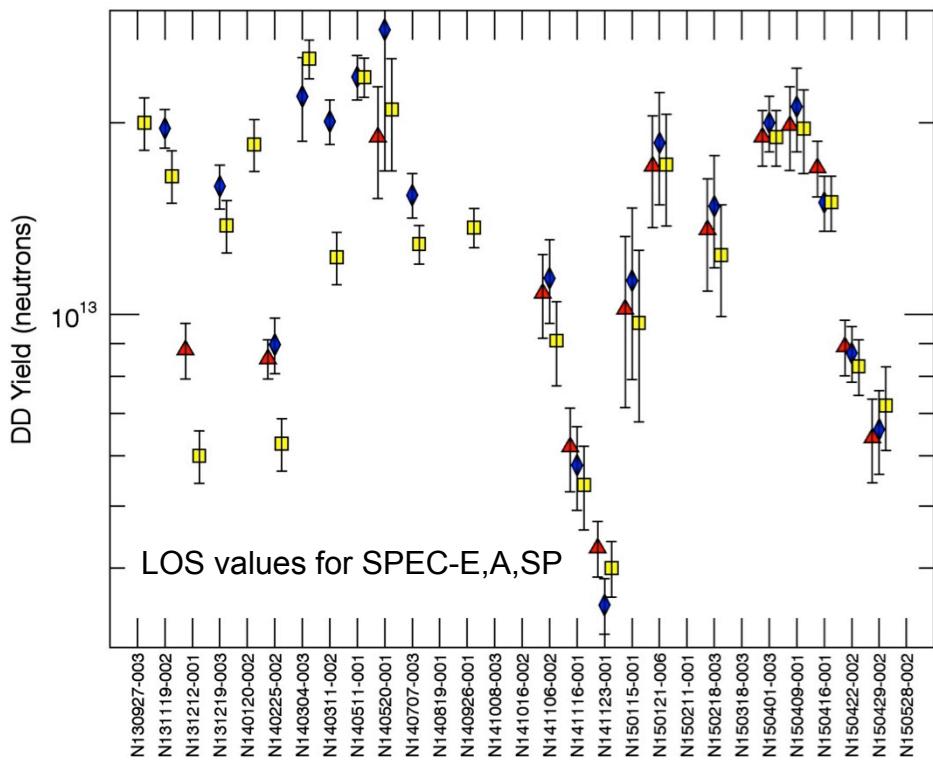
the DT yield is roughly 300 times the DD yield (note yield is not corrected for scattering)

The DT  $T_{ion}$  is higher than the DD  $T_{ion}$

# DT Yield and apparent ion temperature



## DD Yield and apparent ion temperature

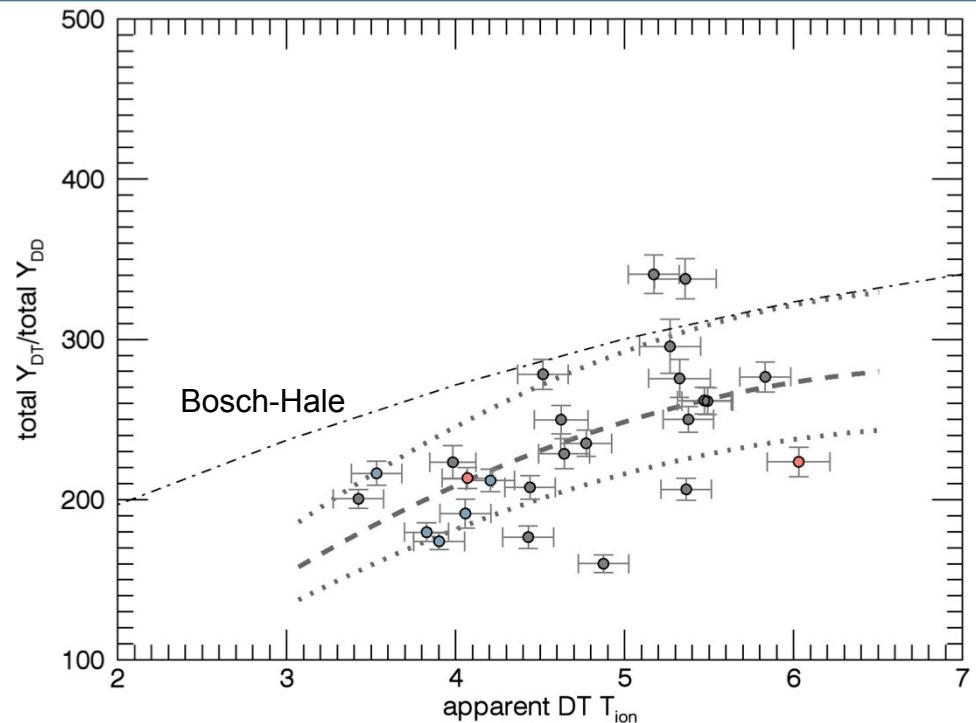


## DD to DT Yield ratio vs. apparent DT ion temperature

Correct the DD and DT Yields for scatter using the measured DSR assuming the same for DD and DT neutrons

Uncertainties are “statistical” for the yield ratio

Dashed line is polynomial “trend” of data, dotted lines are the “systematic” uncertainties.



Yield ratio less than the naïve expectation based on reactivity alone.

## Line-of-sight apparent $T_{\text{ion}}$ variation

LOS variations may hint at anisotropic fuel velocity distributions.

Estimate the sigma of  $N$  LOS measurements as:

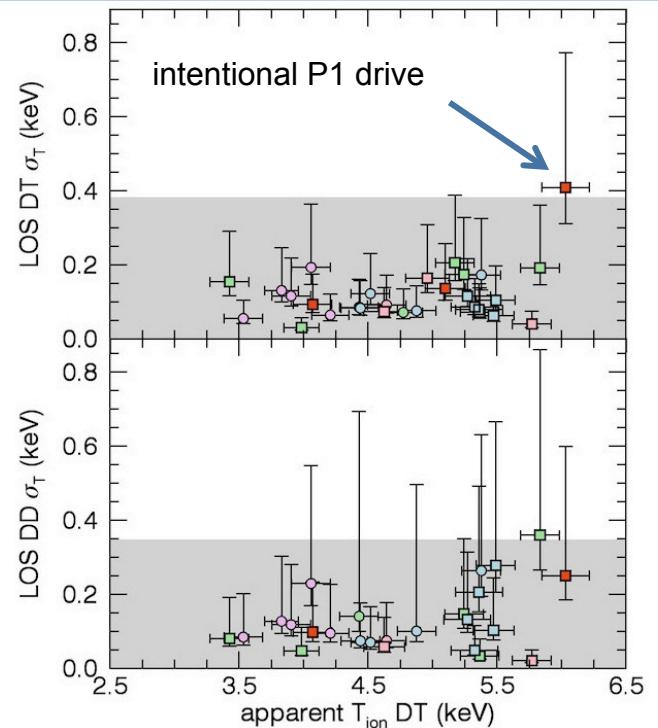
$$\sigma = \sqrt{\frac{(N - 1) \text{ r.m.s.}^2}{\chi_{N-1}^2(\alpha)}}$$

$$\text{r.m.s.} = \sqrt{\frac{1}{N} \sum_{i=1}^N (q_i - \langle q \rangle)^2}$$

$$\chi_{N-1}^2 = \sum_{i=1}^N \frac{(q_i - \langle q \rangle)^2}{\sigma^2}$$

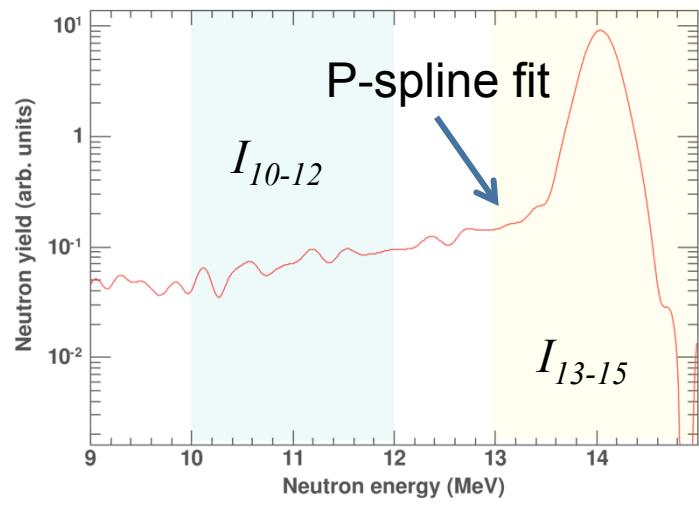
Gray region is systematic uncertainty.

Vertical bars are 68% Confidence Interval ( $\alpha = 0.16$ )

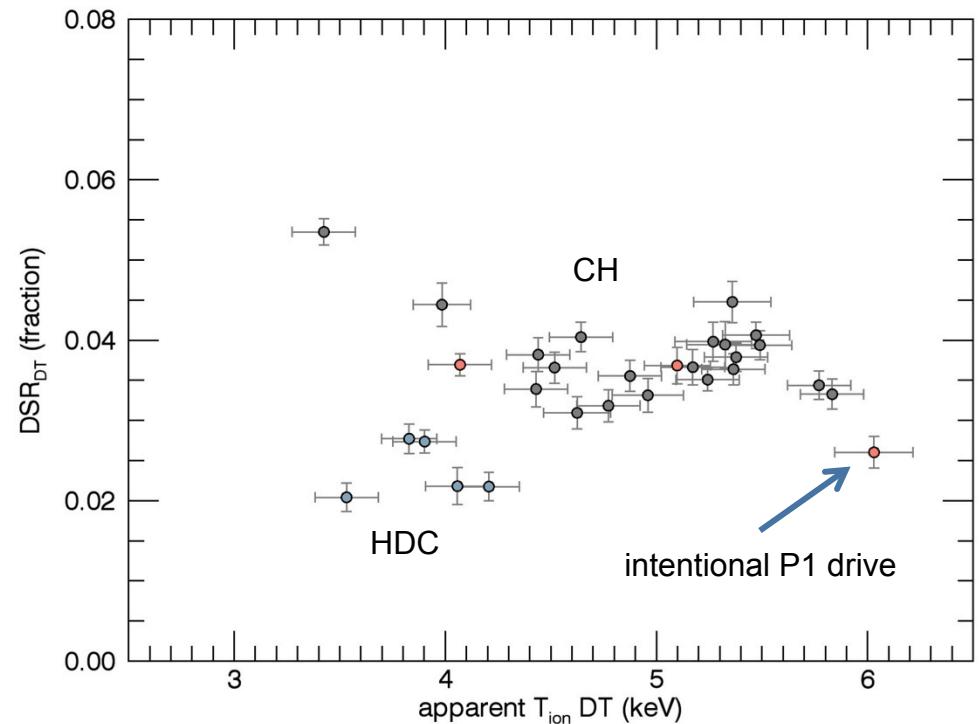


LOS  $\sigma$  is less than 400 eV, individual shots have  $\sigma_{DT}$  less than 200 eV.

## DT DSR



$$\text{DSR} = I_{10-12} / I_{13-15}$$



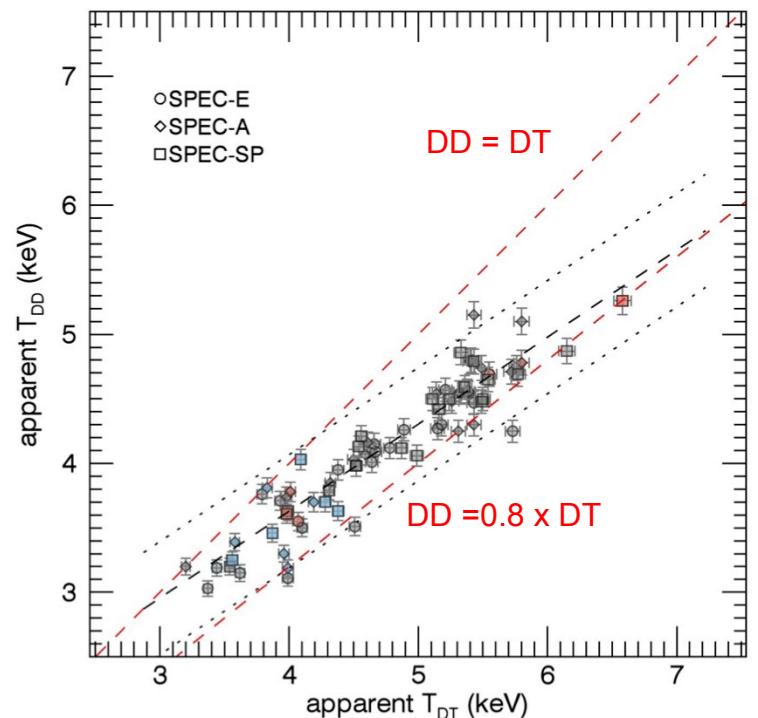
DT DSR not strongly dependent on “drive”

## Apparent DD $T_{\text{ion}}$ vs. DT $T_{\text{ion}}$

The individual LOS measurements are plotted with “statistical” uncertainties.

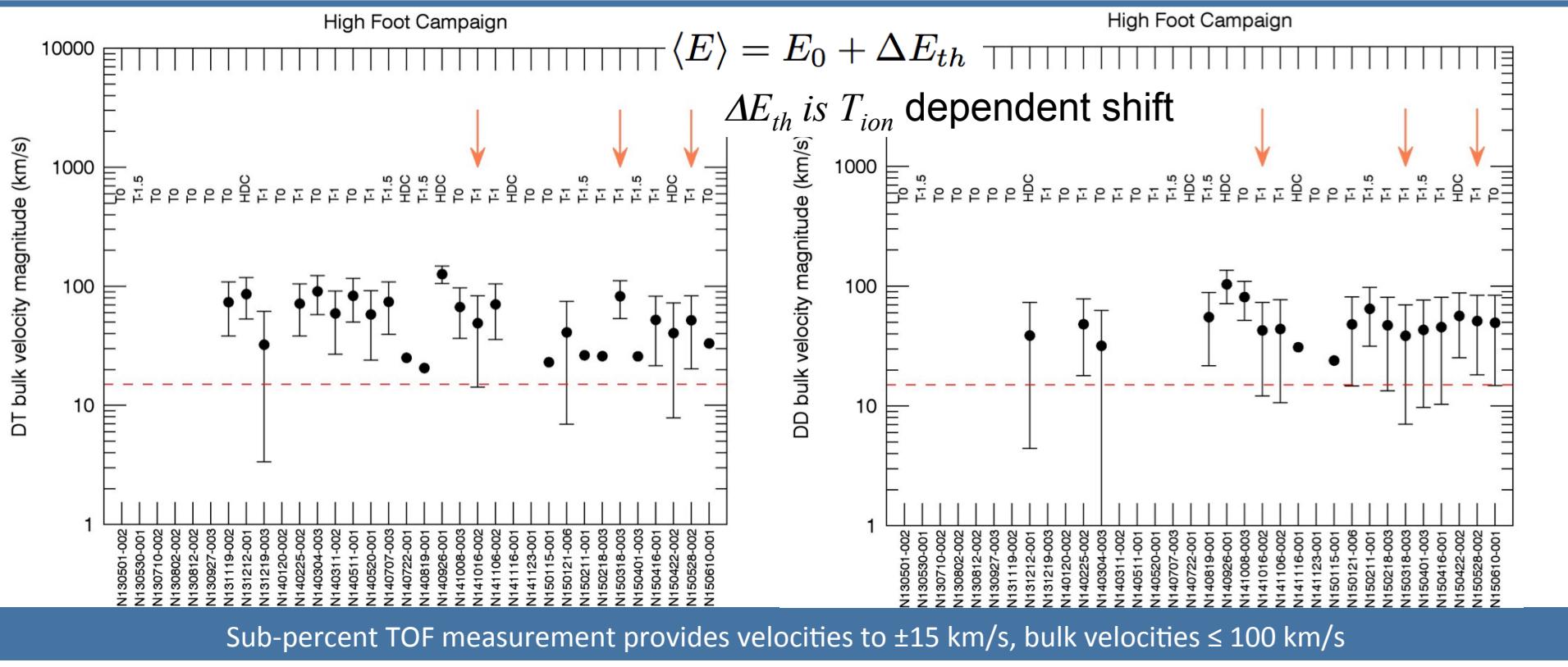
Dashed line is the linear trend of the points.

Dotted lines are the upper and lower “systematic” uncertainty boundaries.

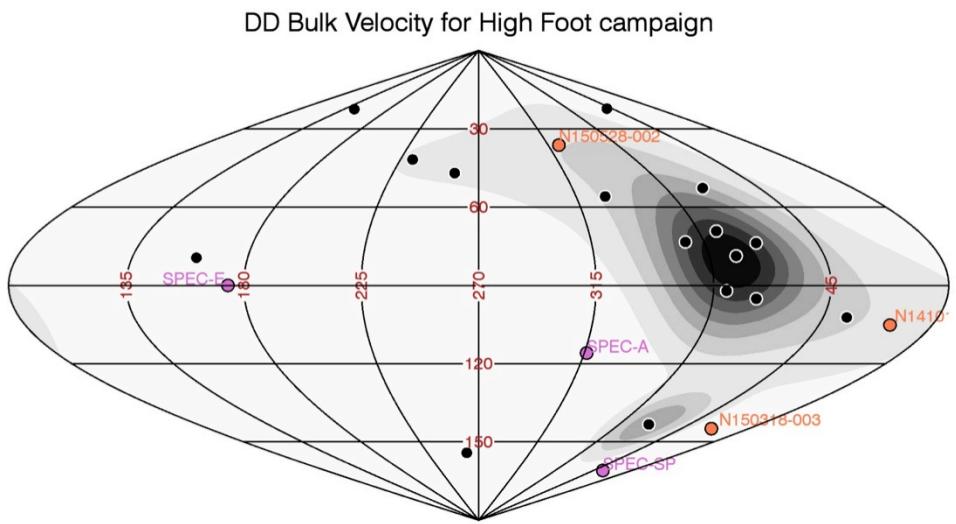
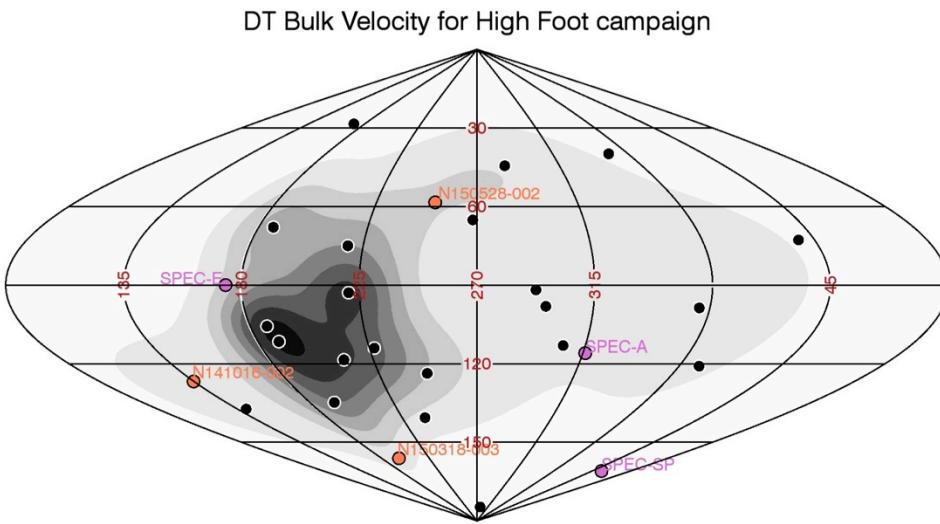


Naïve expectation that the DD and DT  $T_{\text{ion}}$  should be the same, they are not.

# Bulk velocity magnitude



## Bulk velocity “sky maps”



Contours indicate summed probability assuming a gaussian PDF for each shot and summing the PDFs over the sky.

Expect DD and DT velocity directions to correspond, “temperature shift” may be problem.

## Conclusions

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Data derived from the neutron spectrum of High Foot implosion shots do not conform to the naïve expectations when DD and DT spectra are compared.

No simple model of the implosions provides an explanation that is consistent with the nuclear data measurements.

High resolution, 3-D simulations indicate that velocity distributions as well as temporal and spatial variations of plasma density and temperature distributions may provide an explanation. However, the limited statistics of the simulation data set prevents statistically meaningful comparisons at this time.



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